Section 22a

Validation of NASA's First Autonomous Formation Flying Experiment

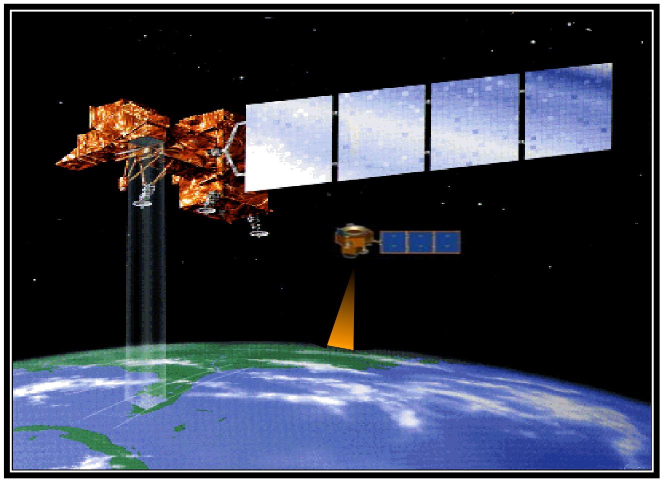
. . . David Folta / John Bristow

Flight Dynamics Analysis Branch, NASA Goddard Space Flight Center

. . . Albin Hawkins / Greg Dell

a.i. solutions, Inc.

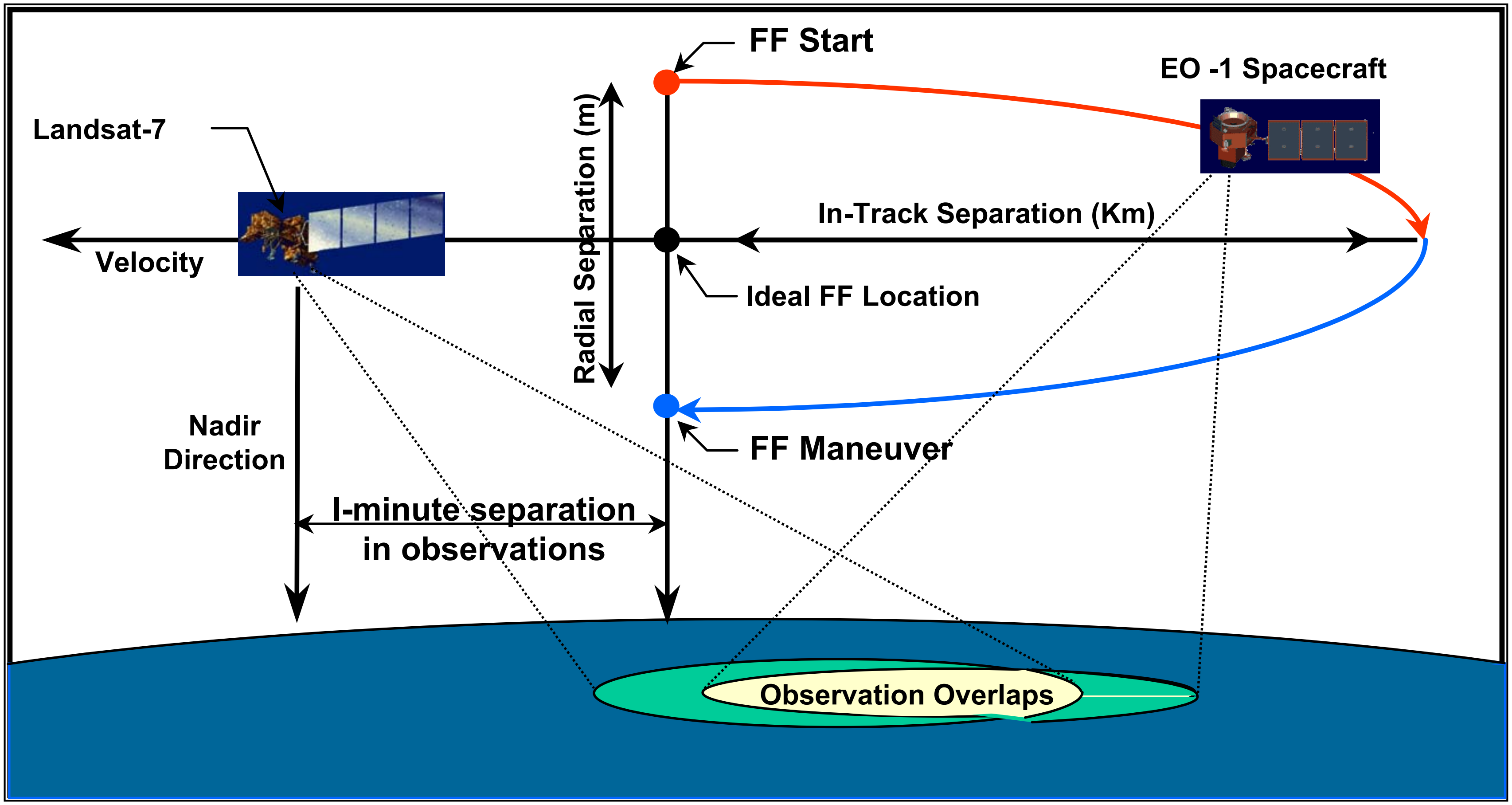
EO-1 GSFC Formation Flying New Millennium Requirements



- ***Enhanced Formation Flying (EFF)***
  - *The Enhanced Formation Flying (EFF) technology shall provide the autonomous capability of flying over the same ground track of another spacecraft at a fixed separation in time.*
- ***Ground track Control***
  - *EO-1 shall fly over the same ground track as Landsat-7. EFF shall predict and plan formation control maneuvers or Δa maneuvers to maintain the ground track if necessary.*
- ***Formation Control***
  - *Predict and plan formation flying maneuvers to meet a nominal 1 minute spacecraft separation with a ±6 seconds tolerance. Plan maneuver in 12 hours with a 2 day notification to ground.*
- ***Autonomy***
  - *The onboard flight software, called the EFF, shall provide the interface between the ACS / C&DH and the AutoCon™ system for Autonomy for transfer of all data and tables.*

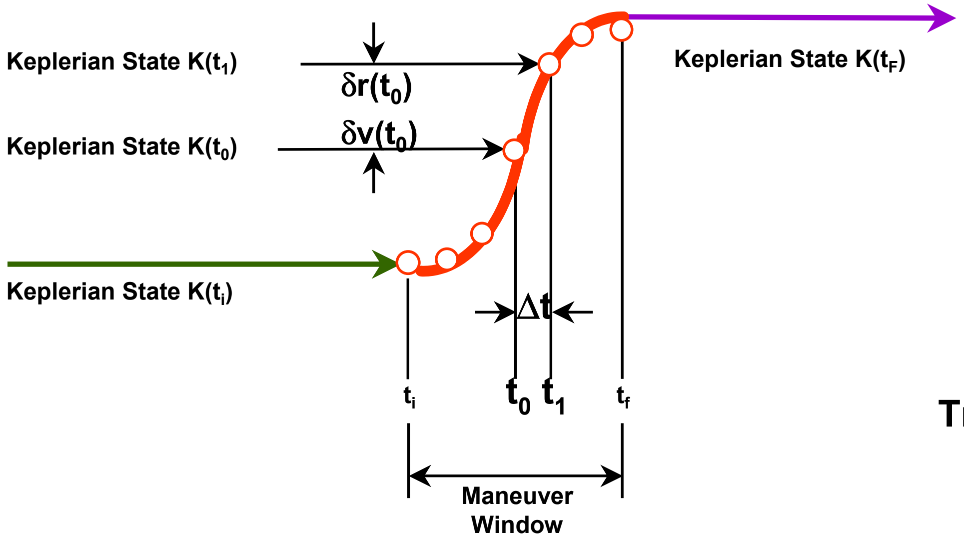
Formation Flying Maintenance Description

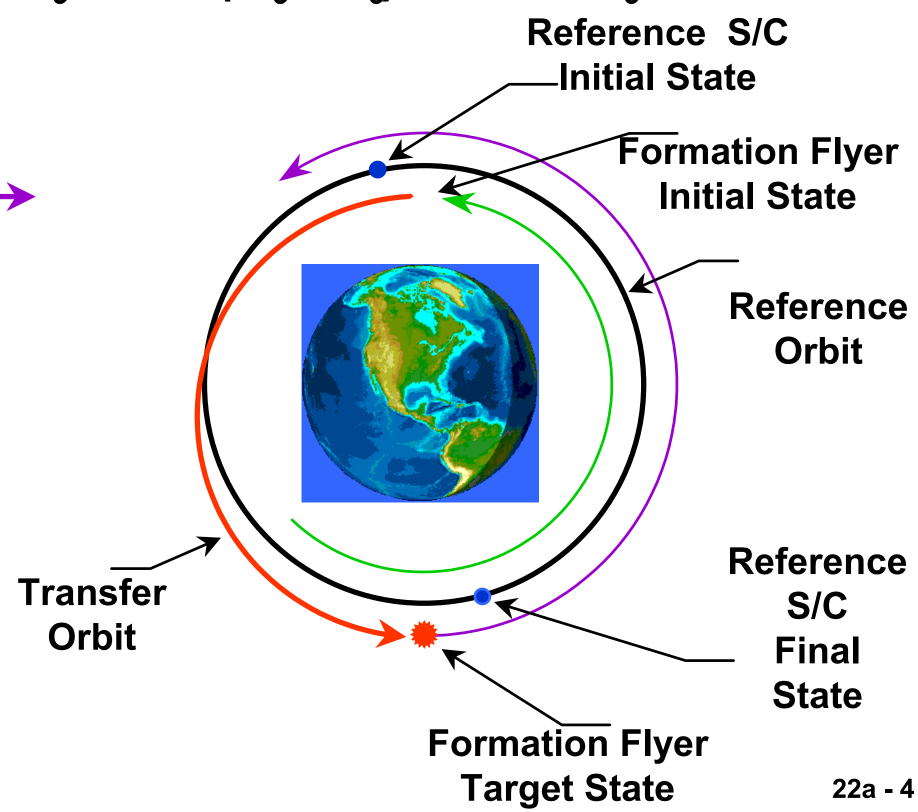
Landsat-7 and EO-1



EFF GSFC (FQ) Algorithm

- ***Find (R_0, V_0) at time t_0 on the reference path - Current State***
- ***Find (R_1, V_1) at time t_1 on the transfer path - Target State***
- ***Project (R_1, V_1) through $(-\Delta t)$ to find (r_0, v_0) at time t_0 - 'Wished' State without ΔV***
- ***Compute δr_0 from $(R_0 - r_0)$ and δv_0 from $(V_0 - v_0)$ at time t_0***





EFF GSFC (FQ) Algorithm

- ***Compute the matrices*** $\left[\mathrm{R}(\mathrm{t}_1)\right]$, $\left[\mathrm{R}(\mathrm{t}_1)\right]$ ***according to the following:***

$$\Phi(t_0,t_1) \equiv \begin{bmatrix} \Phi_1(t_0,t_1), \Phi_2(t_0,t_1) \\ \hline \Phi_3(t_0,t_1), \Phi_4(t_0,t_1) \end{bmatrix} = \begin{bmatrix} \tilde{R}^*(t_0), R^*(t_0) \\ \hline \tilde{V}^*(t_0), V^*(t_0) \end{bmatrix} = \begin{bmatrix} V^T(t_1), -R^T(t_1) \\ \hline -\tilde{V}^T(t_1), \tilde{R}^T(t_1) \end{bmatrix} = \Phi(t_1,t_0)^{-1}$$

$$\left[\mathbf{R}(t_1)\right] = \frac{\mathrm{r}_0}{\mu}(1-\mathrm{F})\left[(\mathbf{R}_1 - \mathbf{r}_0)\mathbf{v}_0^T - (\mathbf{V}_1 - \mathbf{v}_0)\mathbf{r}_0^T\right] + \frac{C}{\mu}\left[\mathbf{V}_1\mathbf{v}_0^T\right] + G[\mathbf{I}]$$

$$\left[\tilde{\mathbf{R}}(t_1)\right] = \frac{\mathrm{R}_1}{\mu}\left[(\mathbf{V}_1 - \mathbf{v}_0)(\mathbf{V}_1 - \mathbf{v}_0)^T\right] + \frac{1}{\mathrm{r}_0^3}\left[\mathrm{r}_0(1-\mathrm{F})\mathbf{R}_1\mathbf{r}_0^T + C\mathbf{V}_1\mathbf{r}_0^T\right] + F[\mathbf{I}]$$

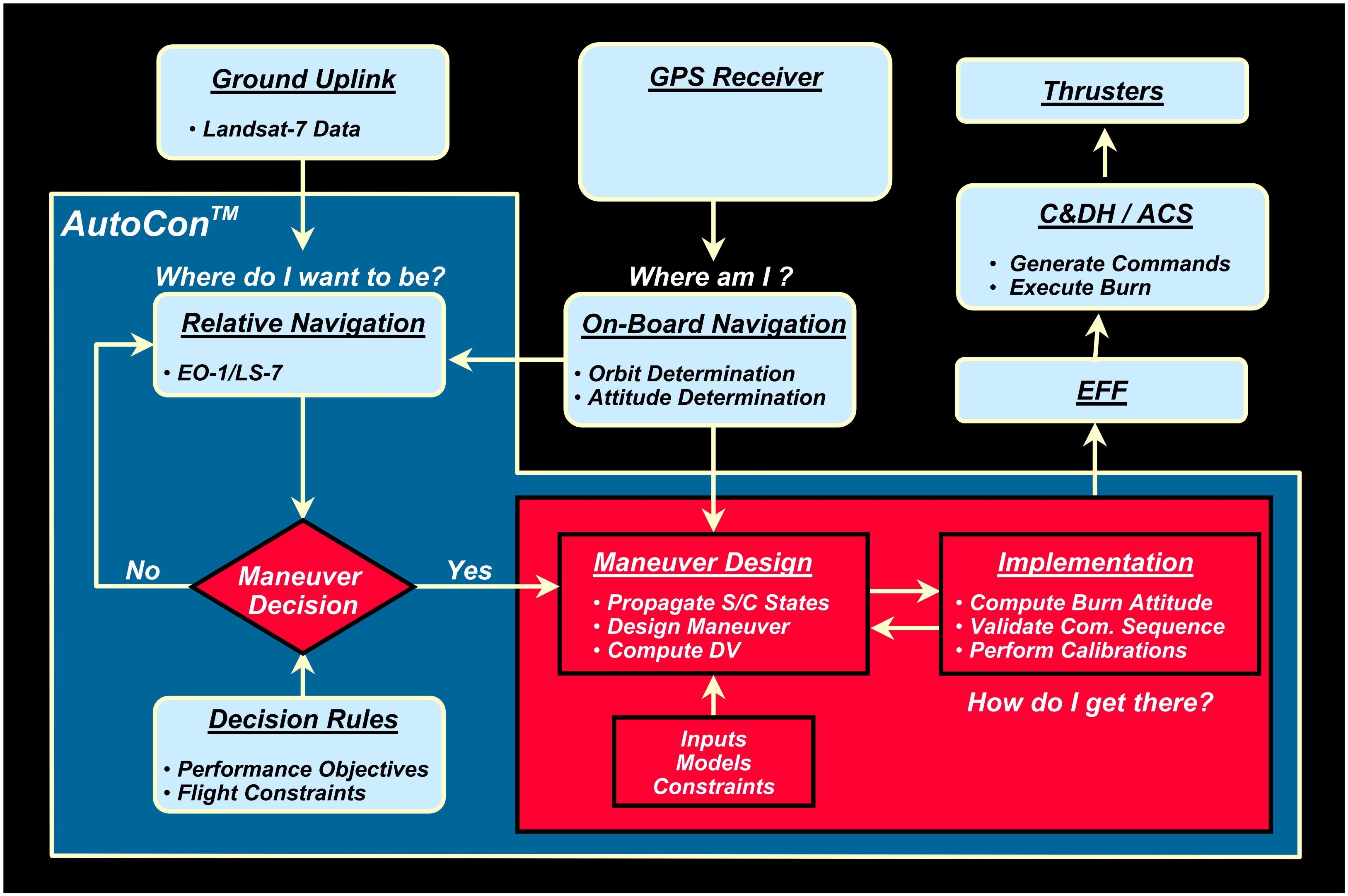
where F and G are found from f & g series through Universal Variables

- ***Compute the 'velocity-to-be-gained'*** **($\mathbf{Dv_0}$)** ***for the current cycle.***

$[R^*(t_0)]$ from $[-R^T(t_1)]$, $[V^*(t_0)]$ from $[R^T(t_1)]$, & $[C^*(t_0)]$ from $[V^*(t_0)]\,[R^*(t_0)]^{-1}$

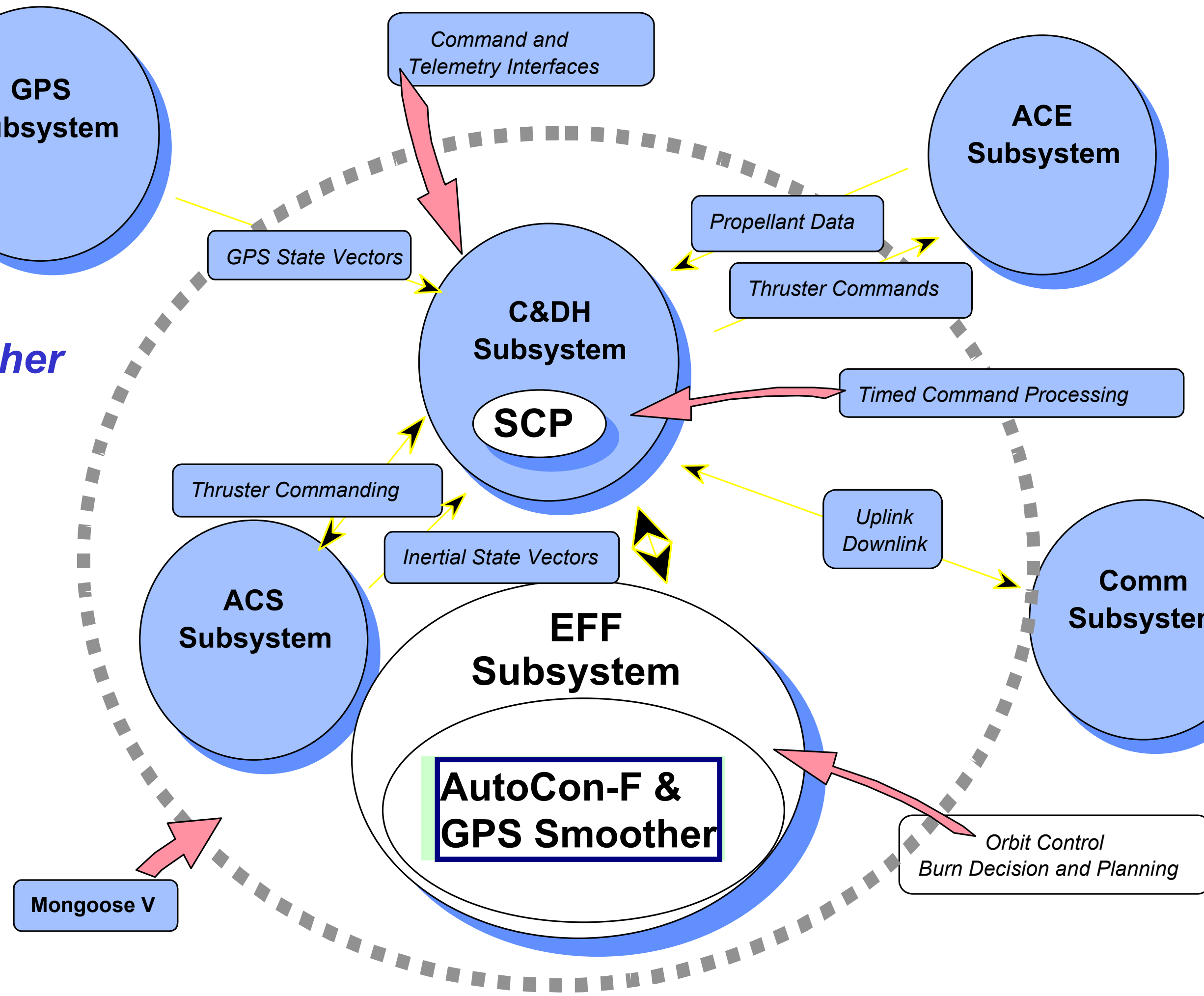
$$\Delta \mathrm{V} = \left[\mathrm{C}^*(t_0)\right]\delta \mathrm{r}_0 - \delta \mathrm{v}_0$$

AutoCon™ Functional Description

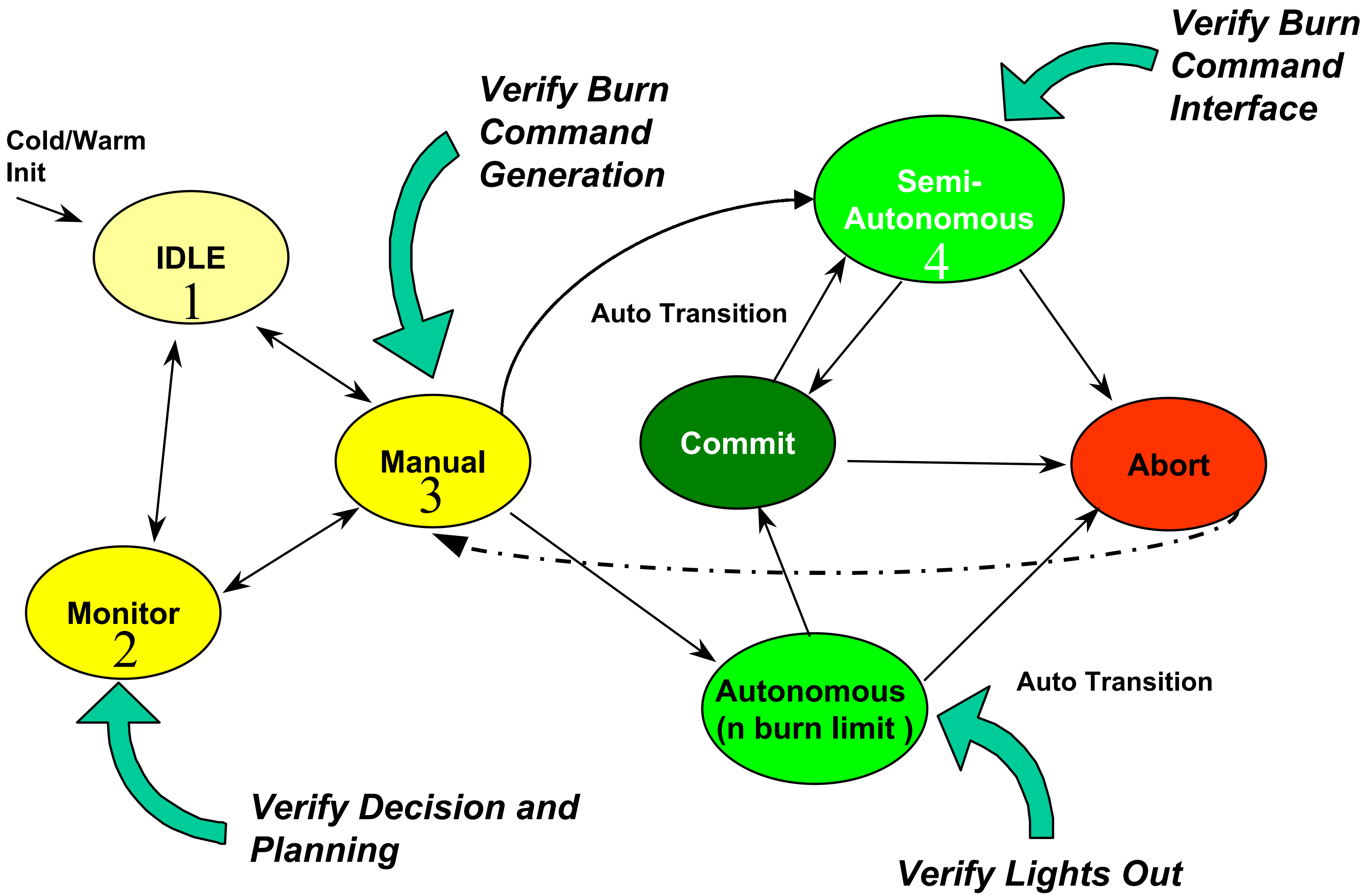


Subsystem Level

- EFF
- AutoCon-F
  - GSFC
  - JPL
  - GPS Data Smoother
- SCP
- Cmd Load

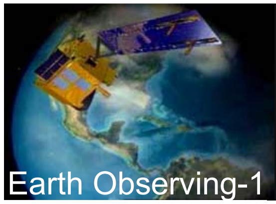


EFF Control Modes Transition Diagram



EFF Verification Approach

- ***Level-1: AutoCon-G***
  - *Using a PC environment to develop, test, provide high fidelity simulations, script development, and proof of concept Fuzzy Logic rules.*
- ***Level-2: Flight Software (FSW) Test Facility***
  - *Using Mongoose Breadboard with FSW, test all interfaces to the ACS and C&DH for telemetry and commanding. Utilized Simulated Tensor Data and noise. Test results compared to similar AutoCon-G results.*
- ***Level-3: Spacecraft***
  - *Using Spacecraft Mongoose, etc., test against actual CPU loading, GPS Constellation Simulator and Tensor, etc. Test results compared with FSW Test Facility results*



EFF Test Results

- ***AutoCon-F/G Benchmark Testing***
  - ***AutoCon-F was benchmarked against AutoCon-G and Windows AutoCon-F for each build***
  - ***Additional AutoCon-G runs against 200 days of Landsat-7 operations***
- ***EFF/AutoCon-F MG5 Testing***
  - ***Will it fit in RAM and execute fast enough on the EO-1 MGV Processor***
  - ***EFF/AutoCon-F interface and numerical accuracy testing performed on the test string from October 1998 to February 2000***
- ***EFF/AutoCon-F Testing on EO-1 (>20 Hours of Testing Onboard)***
  - ***EFF/AutoCon-F successfully executed on EO-1 in April 1999***
  - ***Round 1 of CPT in July found increasing time required for maneuver planning and unacceptable CPU utilization***
  - ***Round 2 of CPT on September 1999 passed all test criteria***
  - ***Round 3 of CPT on December 1999 passed all test criteria***
  - ***Round 4 of CPT on January 2000 passed all test criteria***
  - ***EFF/AutoCon-F successfully executed during Thermal Vacuum in October 1999***

EFF CPT Test Results

- ***AutoCon-F GPS Smoother Testing***
  - *Conducted on the Test String Using Simulated Tensor Data*
  - *Tested on Spacecraft in December 1999 Using Real Tensor Data with Simulated GPS Constellation. Smoother frequently restarted acquisition due to numerous zero filled packets. Smoothing cycle unable to complete.*
  - *Retest on Spacecraft in February 2000. Smoothing cycle completed successfully. Results Indicate Correct Filtering and Improved Navigation Accuracy*
- ***Criteria Passed***
  - *GSFC Targeter Produces Valid Maneuver Plan*
  - *GSFC Targeter Maneuver Consistently Reproduced*
  - *JPL Targeter Code Uploaded*
  - *JPL Targeter Produces Valid Maneuver Plan*
  - *CPU Utilization Within Limits*

Configuration Changes

- ***EFF Tested During S/C CPT***
  - *Parsing of execution to minimize CPU utilization - Logic Error*
  - *Code changes for step size control of propagator - Code Error*
  - *Storing of Spacecraft State Table - Initialization Error*
  - *GPS Leap Second Sign change - Logic Error*
- ***EFF Tested in Thermal Vacuum***
  - *No Changes Made*
- ***Positive Independent Verification Of EFF made using test bed and ground software, AutoCon-F/G***
- ***Upgrades made to Targeter (Delta-v Correction in 2nd Burn) to compensate for the maneuver quantization made by the onboard ACS software for Maneuver duration.***
  - *Minimum code change for maneuver quantization and target state generation*
  - *Targeter executed over 57000 cases to evaluate accuracy over various orbit and targeting conditions*

EFF Control Modes (1 of 2)

- ***Idle***
  - *Pending on incoming data and send it to the bit bucket.*
  - *Otherwise do nothing*
- ***Monitor - (AutoCon can Execute with maximum safety for S/C)***
  - *Invoke AutoCon only*
  - *Just report maneuver planning data to ground*
  - *No maneuver commands are generated*
- ***Manual - (AutoCon can Execute with Ground as safety)***
  - *Generate maneuver commands (table loads) and send to ground only*
  - *All burns must be commanded from the ground in their entirety*
  - *Ground can loopback command from EFF telemetry if desired to execute burn*
- ***Semi-Autonomous - (Ground still in loop for go/nogo)***
  - *Send maneuver commands (table loads) to the SCP*
  - *Do not enable ATS,RTS in SCP of C&DH*
  - *Must switch to Commit Mode to allow loaded burn to execute*
  - *Inaction will cause loaded burn to expire*

EFF Control Modes *(2 of 2)*

- ***Commit - (allow an EFF loaded burn to execute)***
  - ***Enable ATS and RTSs in SCP to <u>permit loaded burn to be executed</u>***
  - ***Required at least two hours before time of burn***
  - ***Autonomously switch to Semi-Autonomous Mode upon completion***
- ***Abort - (abort an EFF loaded burn and clean up)***
  - ***Disable the ATS and RTSs in SCP to <u>prevent execution of burn</u>***
  - ***<u>Clean up from any preparation for burn</u>***
  - ***Autonomously switch to Manual Mode upon completion***
- ***Autonomous - (allow EFF to control the orbit)***
  - ***Closed loop orbit maintenance.***
  - ***Use Commit Mode to switch back to Semi-Autonomous Mode and not abort a planned burn***
  - ***<u>Ground can still monitor with 24 hour notice to burn</u>***
  - ***Switch to Semi-Autonomous Mode after N burns. Safety for unattended operation***

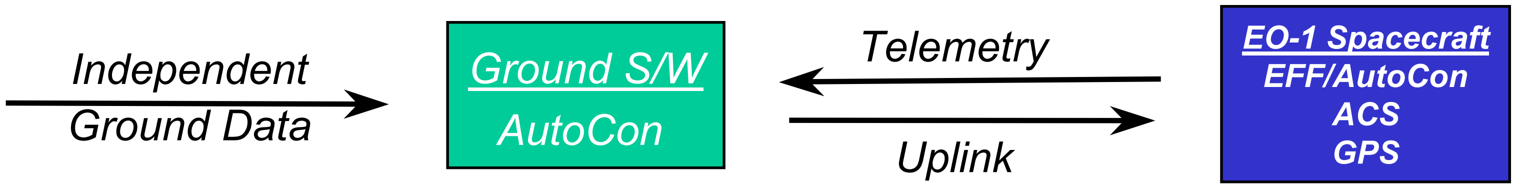
EFF Onboard Validation Timeline

- ***Launch***
  - *EFF Idle*
  - *Collect and analyze GPS Data*
- ***Checkout***
  - *EFF Monitor - Check GPS Smoother*
  - *EFF Monitor - Check Targeter Planning*
  - *EFF Monitor - Compare Onboard Plan with routine Ops*
  - *EFF Manual - Compare plans and submit AutoCon-F to execute burn pair*
- ***Routine Ops***
  - *EFF Semi-Auto - Compare and allow to execute Maneuver*
  - *EFF Autonomous - N=1, N=?*

Execution Scenario

- ***Flight interface every 1 second***
  - *Read ACS, GPS, and ACE data*
  - *Thin data and extract significant events*
- ***EFF/GSFC executes every 12 hours or EFF/JPL executes continuously***
  - *Decide if Maneuver required*
  - *If required, calculate desired maneuver and generate commands*
- ***Executes to capture significant events***
  - *Equator crossings*
  - *Time elapsed*
  - *Landsat-7 State Vector*

Onboard Algorithm Validation



- ***All validation objectives can be met by independent ground comparison. Conforms to ground independent checking using AutoCon-G & FreeFlyer or the FF test bed using AutoCon-F.***
- ***Execute algorithm onboard with known input data values and allow ground AutoCon to process the data using the Fuzzy Logic Control Algorithms.***
- ***Algorithms will compute the required ΔV and Onboard will notify ground through AutoCon telemetry of maneuver parameters.***
- ***The validation will show that the algorithm logic performs properly, computing intermediate parameters, guidance matrices, maneuver quarterion, and body frame ΔV.***
- ***In monitor/maneuver mode: collect tensor data and compare against ground smoother, change script to generate maneuver plan every six hours (26 burns plans per week) for consistency check***

EFF Verification Matrix

Test Phase	Test Description	Completed	Passed
Phase I (Development)			
D-1 : Propagation with forces	Correct Prop Models	2/17/99	Yes
D-2 : Two-body propagation	Targeter Prop Model	2/17/99	Yes
D-3 : Conditional constraint check	Formation Constraints	2/17/99	Yes
D-4 : GSFC targeter	Folta/Quinn Algorithm	2/17/99	Yes
D-5 : JPL targeter	JPL Algorithm	2/17/99	Yes
D-6 : O-C maneuver calibration	DV Calibration via States	2/17/99	Yes
D-7 : Data smoother	GPS Position Smoother	2/16/99	Yes
Phase II (Simulation)			
S-1 : Propagation with forces	Correct Prop Models	2/22/99	Yes
S-2 : Two-body propagation	Targeter Prop Model	2/22/99	Yes
S-3 : Conditional constraint check	Formation Constraints	2/22/99	Yes
S-4 : GSFC targeter	Folta/Quinn Algorithm	2/22/99	Yes
S-5 : JPL targeter	JPL Algorithm	6/28/99	Yes
S-6 : O-C maneuver calibration	DV Calibration via States	2/22/99	Yes
S-7 : Data smoother	GPS Position Smoother	2/17/99	Yes
Phase III (Flight)			
F-1 : GSFC targeter	Folta/Quinn Algorithm	9/1/99	Yes
F-2 : GPS Data Smoother	GPS Position Smoother	2/00	Yes
F-3 : JPL targeter upload & exec	Upload of JPL algorithm	9/1/99	Yes

CPT Test Timeline

- ***2353L EFF_cpt.prc started***
- ***0004L Table upload complete***
- ***0016L GSFC targeter produced first maneuver plan***
- ***0025L GSFC targeter produced identical maneuver replan***
- ***0025L JPL targeter code uploaded started***
- ***0115L JPL targeter code upload completed and JPL maneuver planning started***
- ***0200L JPL targeter produced maneuver***
- ***0201L GSFC targeter tables started being reloaded***
- ***0208L GSFC targeter table upload completed and GSFC targeting restarted***
- ***0217L GSFC targeter produced identical maneuver replan***
  - ***0220L Test complete. EFF left running on spacecraft to simulate a heavy load on the spacecraft for the remaining CPT testing.***

Sample Maneuver Scenario

◆ *Burn #1 - 24 Hours* *Setup by EFF*	*Load ATS and RTSs - (to SCP)* *Turn on EVD Thruster Driver Board - (to ACE)*
◆ *Burn #1 - > 2 Hours*	*Ground confirms Burn(s),* *Enable ATS, and RTSs - (to SCP)* *or Commit to EFF or Autonomous EFF*
◆ *Burn #1 - 90 Minutes*	*Enable CATBED Heaters - (to ACE)* *Reset ACS Thruster Counters - (to ACS)*
◆ *Burn #1 - 6 seconds*	*Enable thrusters - (to ACE)*
◆ *Burn #1*	*Delta-V command (to ACS)*
◆ *Burn #1 + 1 minute*	*Disable thrusters - (to ACE)*
◆ *Burn #2 - 6 seconds*	*Enable thrusters - (to ACE)*
◆ *Burn #2*	*Delta-V command (to ACS)*
◆ *Burn #2 + 1 minute*	*Disable thrusters - (to ACE)*
◆ *Burn #2 + 90 seconds* *if #2 not required* *then* *Burn #1 + 90 sec*	*Disable CATBED Heaters - (to ACE)* *EVD Thruster Driver Board Off - (to ACE)* *Disable Delta-V transition - (to ACS)* *Disable RTSs - (to SCP)*

EFF Onboard Verification Timeline

Launch - 1 Month	1 - 2 Months	> 2 Months - 1 Year
Ground Ops Verification	Onboard Cmd Generation Verification	Autonomous

General Test

- *AutoCon Exec*
- *Fuzzy Logic*
- *Maneuver Decision*
- *Maneuver Planning*

Ground Ops Verification

- *Onboard General Test: Input / Output / Uploads, etc.*
- *I/F Verification with ACS / C&DH / GPS for data and telemetry*
- *Algorithm verification, maneuver plans and calibration*
- *Pre-maneuver Cmd validation*

Closed Loop

- *Onboard Generation of Commands*
- *Post Maneuver*

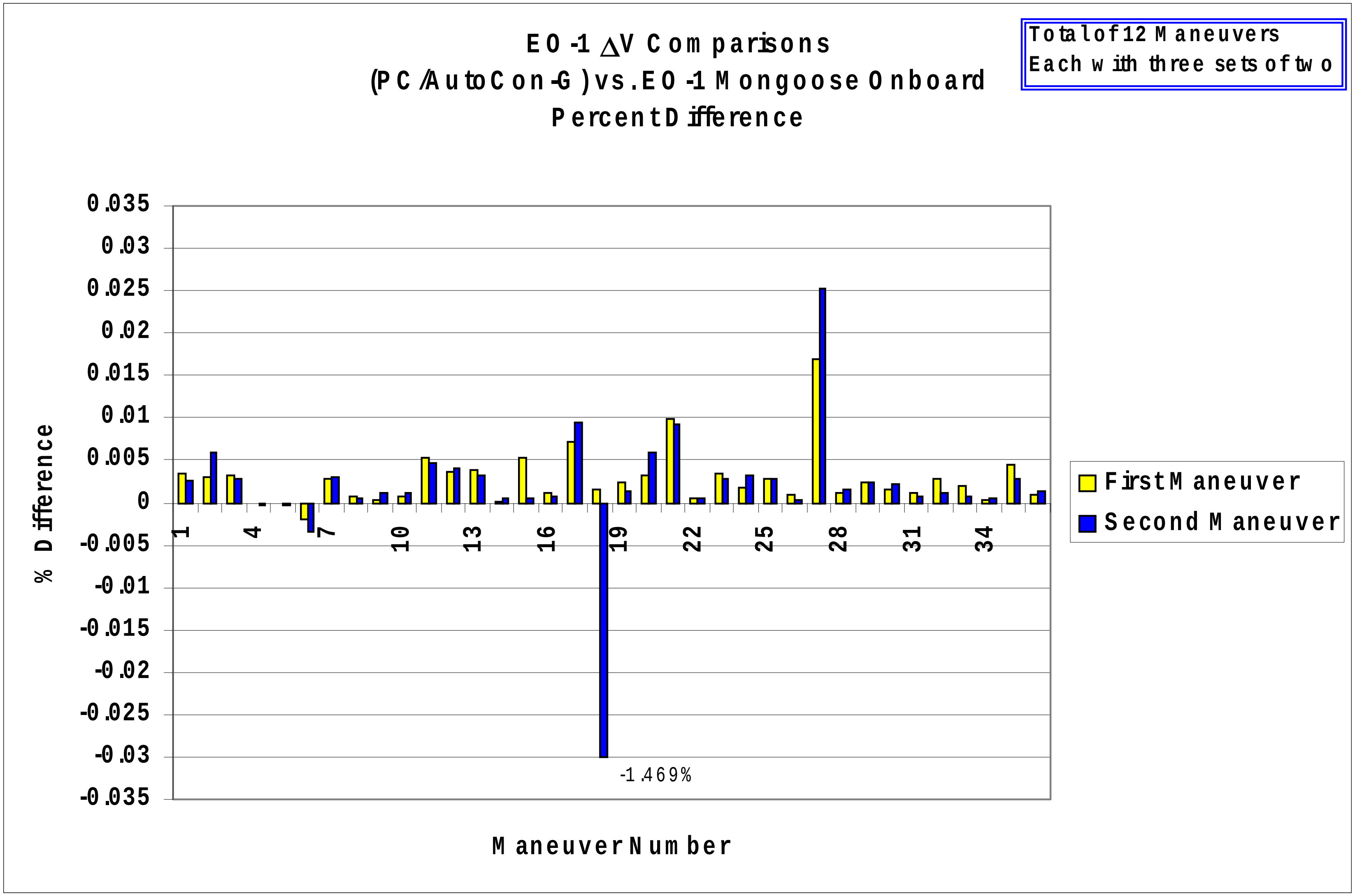
Preliminary Validation Process

- ***Continuous mode operations***
  - *Ingest a GPS state*
  - *Propagate to 12 hours*
  - *Compute a maneuver at epoch based on default target*
  - *Propagate to 24 hours*
  - *Compute a maneuver at epoch based on default target*
  - *Propagate to 48 hours*
  - *Compute a maneuver at epoch based on default target*
- ***Compare onboard ΔV and propagation states to***
  - *Ground Based AutoCon using GPS states with same onboard script*
  - *Original Matlab M-file using states from telemetry data*

Some Validation Notes

- ***Maintenance ΔVs are computed as alongtrack and 3-D with the alongtrack component the applied ΔV***
- ***Finite burn maneuver durations are quantized to 1 second to meet propulsion system requirements***
- ***Second maneuver is computed from a velocity difference of predicted and targeted velocities after applying the first FQ ΔV and an internal propagation. Also takes quantization into account.***
- ***Maneuver magnitude ranged from 0.5cm/s to 2m/s for alongtrack and from 1.6m/s to 133m/s for the 3-D***

Percentage Difference in EO-1 Onboard & Ground ΔVs



Percentage Difference in 3-D EO-1 ΔVs

Earth Observing-1

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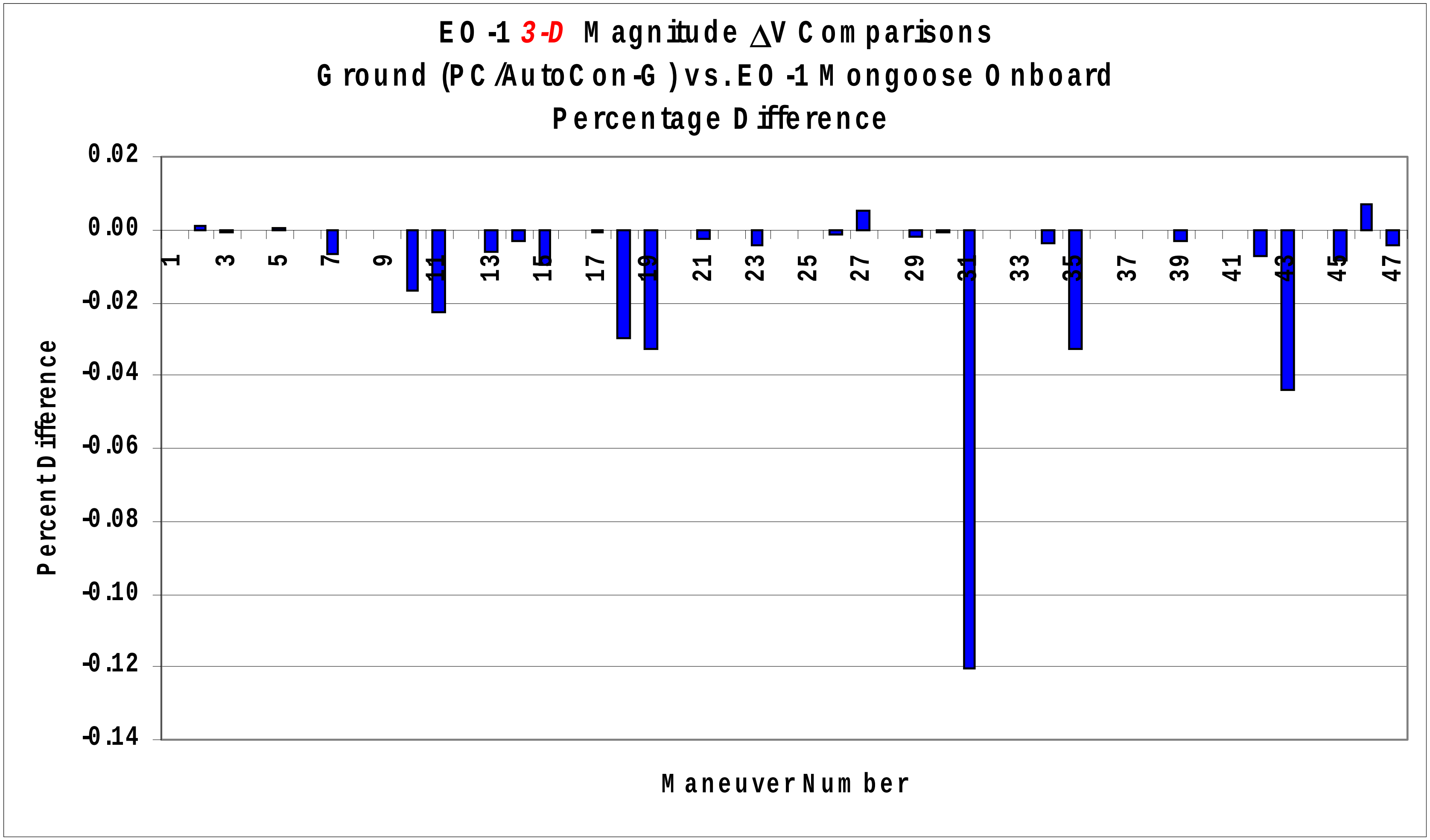
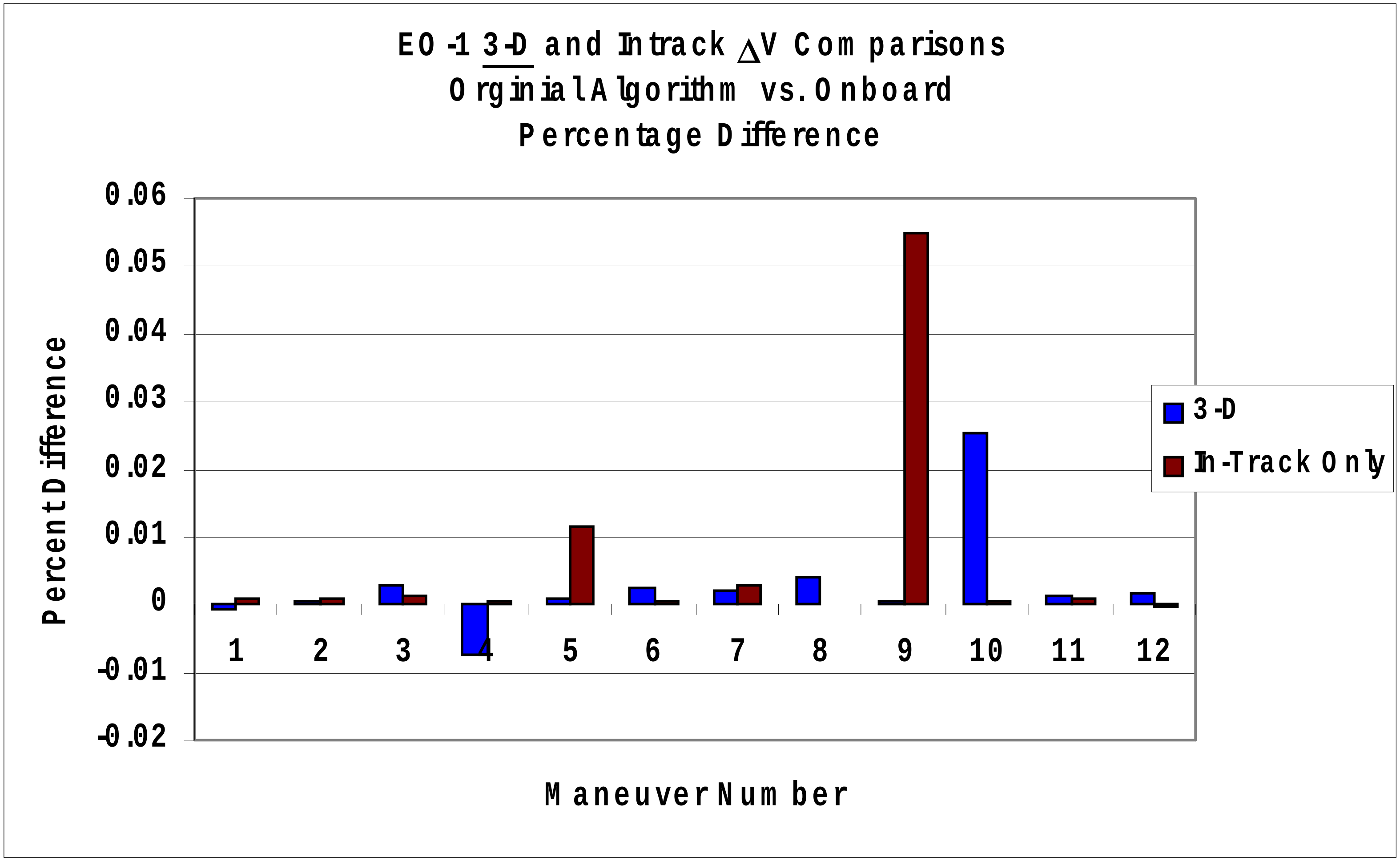
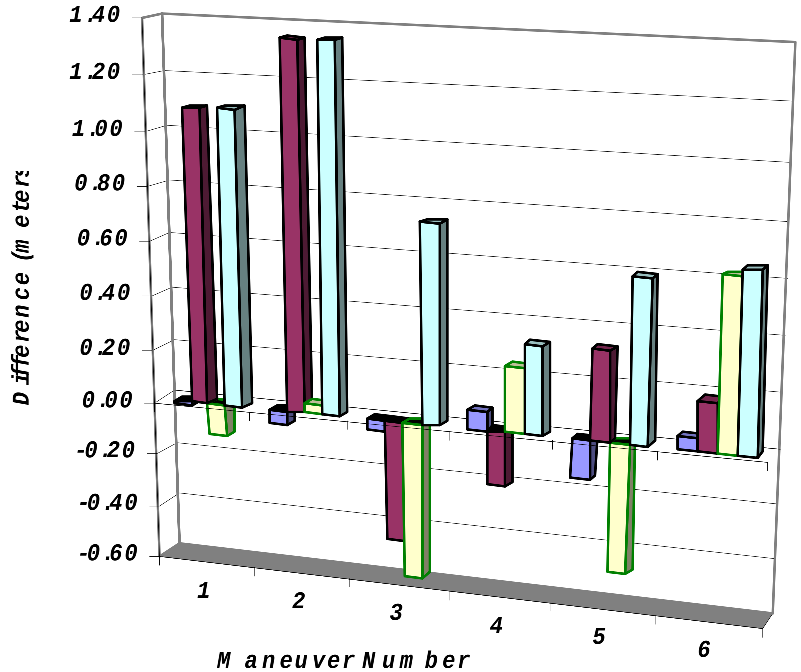


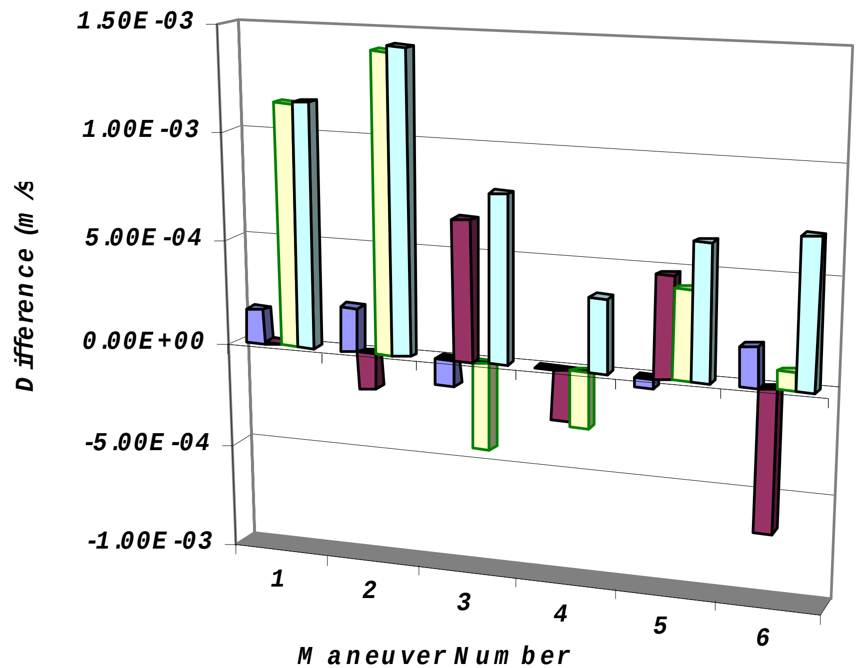
Percentage Difference In Original Algorithm & Onboard



Orbit Propagator Errors for Position & Velocity at 1.5 Orbits



- ***Position Mean = 0.79 m***
- ***Position StDev = 0.37 m***
- ***Velocity Mean = 0.84 m/s***
- ***Velocity StDev = 0.39 m/s***



Difference in EO-1 Onboard & Ground Maneuver Quantized ΔVs

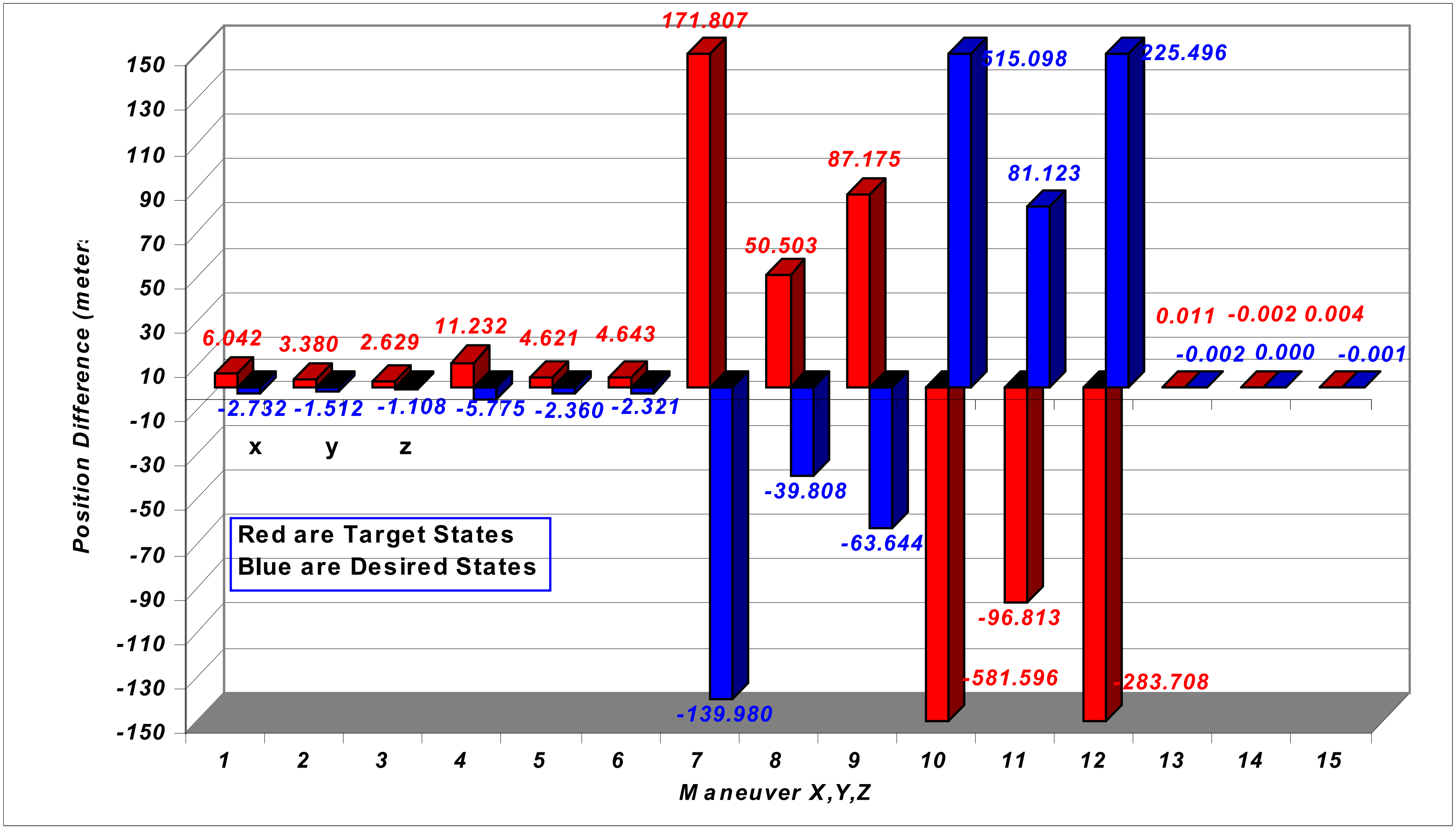
Mode	***Onboard ΔV1 cm/s***	***Onboard ΔV2 cm/s***	***Ground ΔV1 Difference cm/s***	***Ground ΔV2 Difference cm/s***	***% Diff ΔV1 vs. Ground %***	***% Diff ΔV2 vs. Ground %***
Auto	4.9854078	0.0000000	0.0000001	0.0000000	0.00015645	0.00000000
Auto	2.4376271	3.7919202	0.0000003	0.0000002	0.00111324	0.00053176
Semi-Auto	1.0831335	1.6247106	0.0000063	-.0026969	0.05852198	-14.2361365
Semi-Auto	2.3841027	0.2649020	0.0000000	0.0000000	0.00011329	0.00073822
Semi-Auto	5.2980985	1.8543658	-0.0008450	-0.0002963	-1.56990117	-1.57294248
Manual	2.1915358	5.2049883	0.0000004	-0.0332099	0.00163366	-0.00022414
Manual	3.5555711	7.9318735	-0.0000003	-0.0272687	-0.00081327	3.57089537

Note: A final fully autonomous GPS derived maneuver was performed June 28, with preliminary validation results yielding a 0.005% difference in quantized ΔV and similar results in 3-axis

Difference in EO-1 Onboard & Ground Maneuver 3-Axis ΔVs

Mode	Onboard ΔV1 m/s	Ground ΔV1 Difference cm/s	3-axis ΔV1 vs. Gnd %	Algorithm ΔV1 Diff cm/s	3-Axis ΔV1 vs. Alg %
Auto	10.8468	-0.0005441	-0.0000502	0.0003217	0.0000297
Auto	11.8633	0.0178726	0.0015066	-0.0101756	-0.0008577
Semi-Auto	12.6416	0.0311944	0.0024677	0.0091362	0.0002867
Semi-Auto	14.7610	0.1888158	0.0127932	0.0000000	0.0001196
Semi-Auto	15.3797	-0.2526237	-0.0164231	-0.0633549	-0.0045164
Manual	15.5790	10.4109426	0.6682668	-0.0117851	-0.0007565
Manual	15.4749	0.0018465	0.0001193	-0.0307683	-0.0021934

Difference in Position for Desired & Target States



Earth Observing-1

Formation Data from Definitive Navigation Solutions *(1 of 3)*

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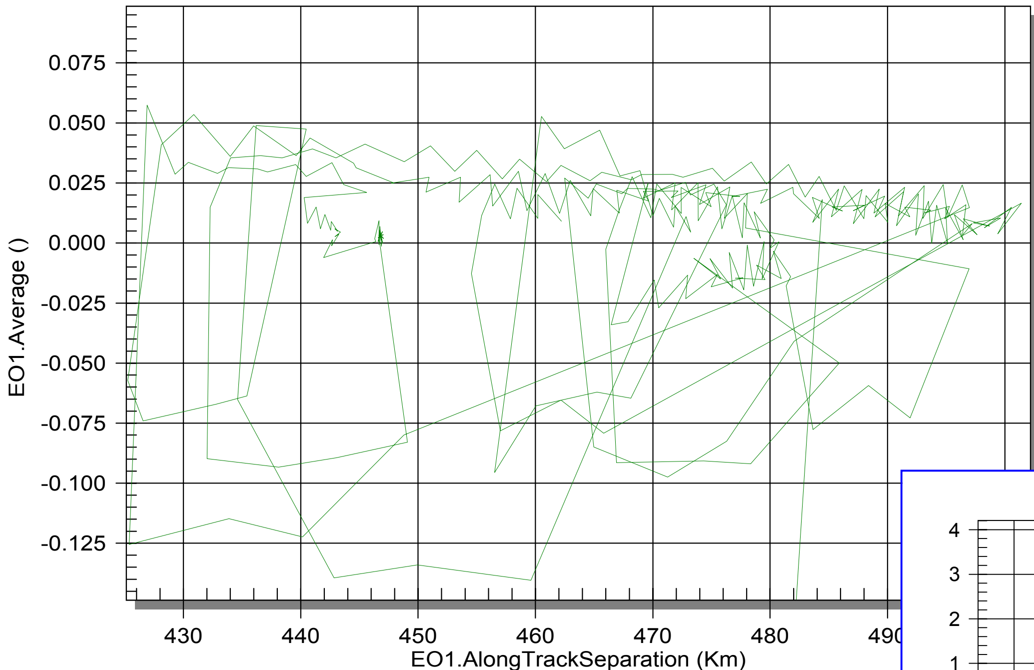
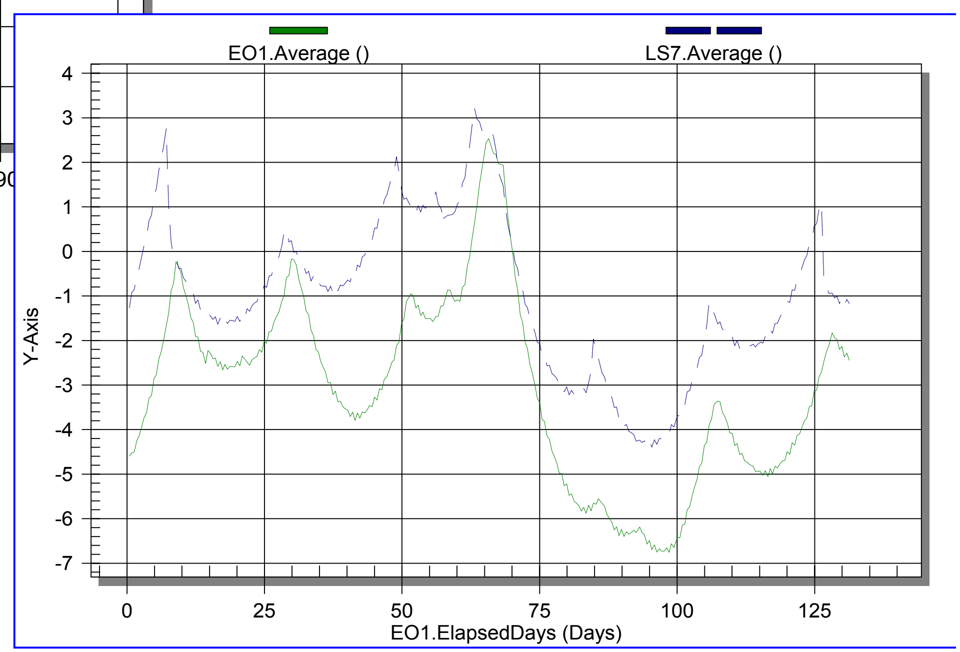


Radial vs. alongtrack separation over all formation maneuvers (range of 425-490km)

Groundtrack separation over all formation maneuvers maintained to 3km



Earth Observing-1

Formation Data from Definitive Navigation Solutions (2 of 3)

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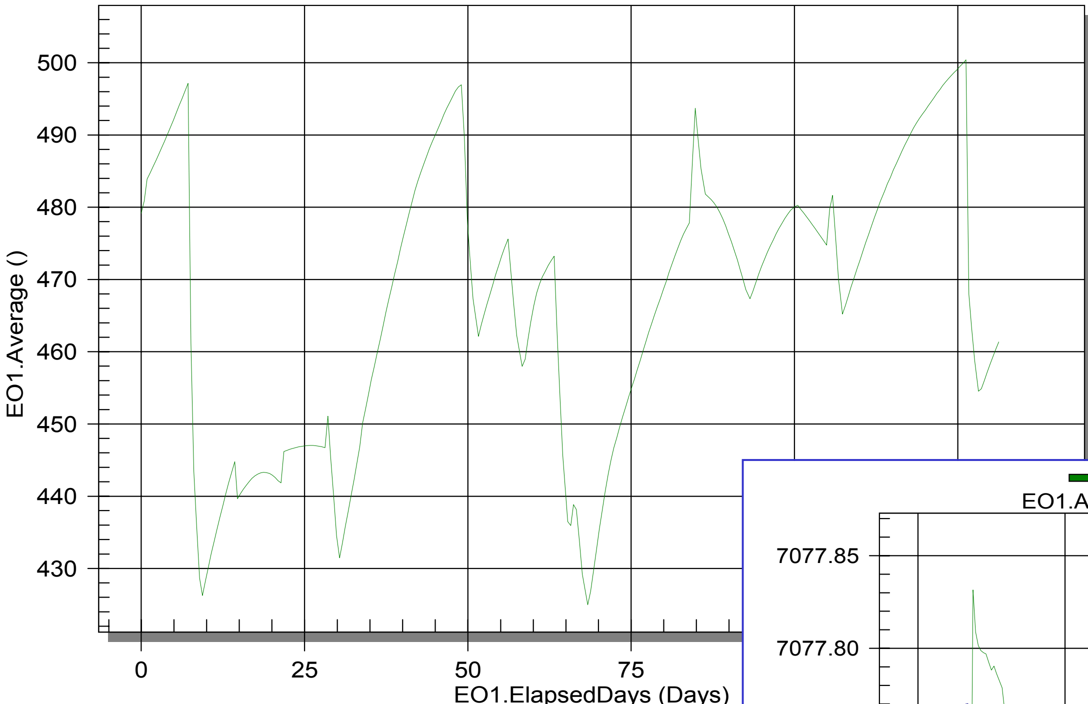
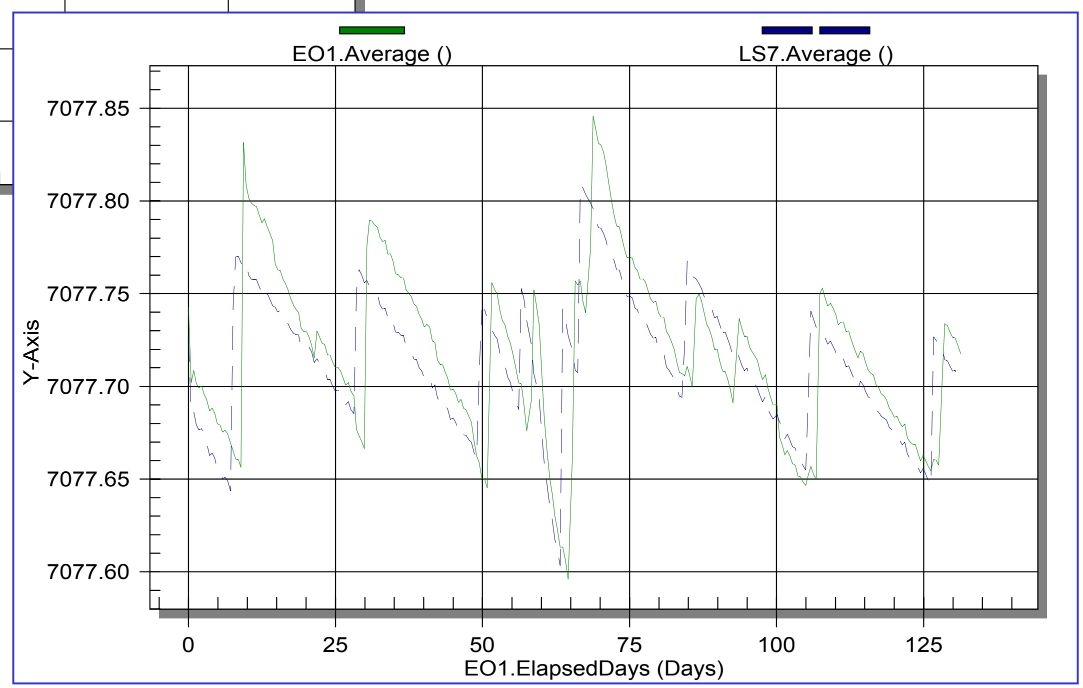
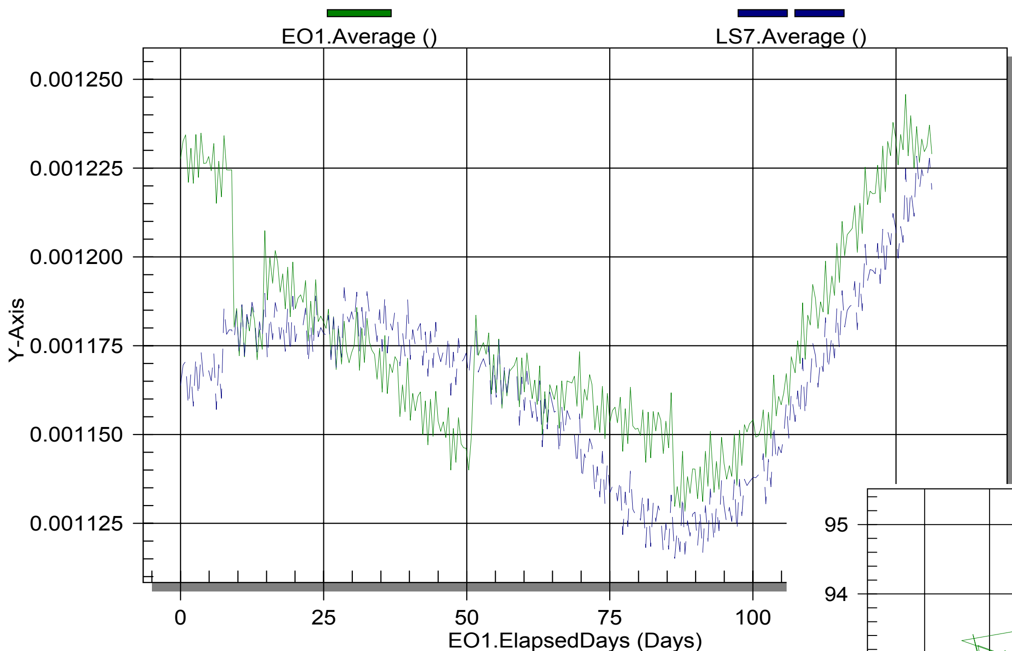


Alongtrack separation vs. Time over all formation maneuvers (range of 425-490km)

Semi-major axis of EO-1 and Landsat-7 over all formation maneuvers

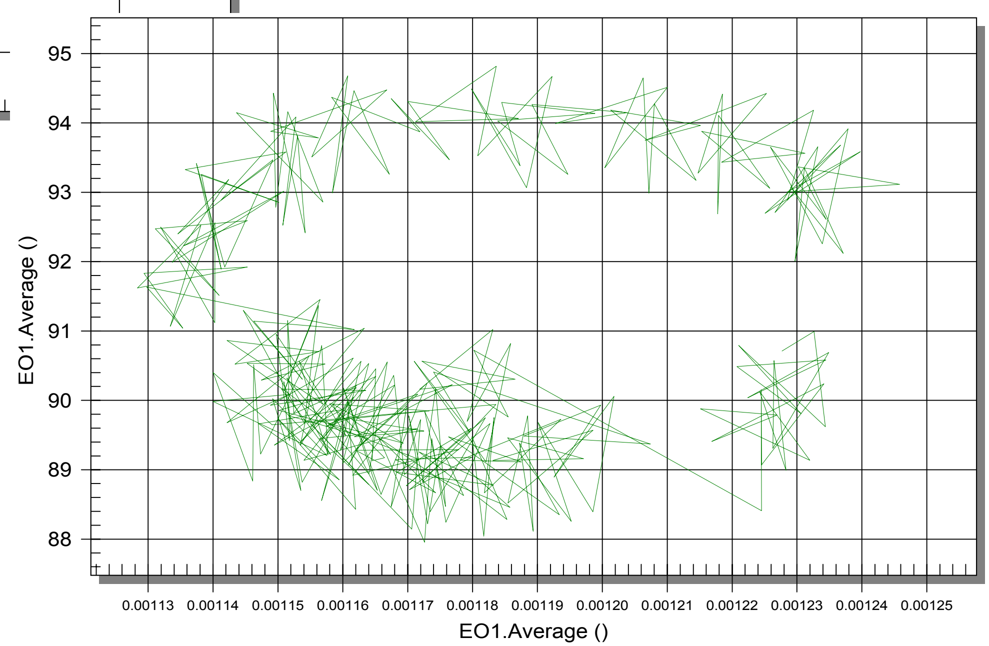


Formation Data from Definitive Navigation Solutions (3 of 3)



Frozen Orbit eccentricity over all formation maneuvers (range of .001125 - 0.001250)

Frozen Orbit w vs. eccentricity over all formation maneuvers with range of 90+/- 5 deg.



Summary / Conclusions

- ***A demonstrated, validated fully non-linear autonomous system for formation flying***
- ***A precision algorithm for user defined control accuracy***
- ***A point-to-point formation flying algorithm using discretized maneuvers at user defined time intervals***
- ***A universal algorithm that incorporates***
  - ***Intrack velocity changes for semi-major axis control***
  - ***Radial changes for formation maintenance and eccentricity control***
  - ***Crosstrack changes for inclination control or node changes***
  - ***Any combination of the above for maintenance maneuvers***

Summary / Conclusions

- ***A system that incorporates fuzzy logic for multiple constraint checking for maneuver planning and control***
- ***Single or multiple maneuver computations***
- ***Multiple / generalized navigation inputs***
- ***Attitude (quaternion) required of the spacecraft to meet the ΔV components***
- ***Proven executive flight code***

Bottom Line:

Enabling Future Formation Flying / Multiple Spacecraft Missions